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Review

Transition from building information modeling (BIM) to integrated digital delivery (IDD) in sustainable building management: A knowledge discovery approach based review

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A B S T R A C T

Over the past decade, building information modeling (BIM) and sustainability have attracted increased interest, with a concomitant rise in the number of related publications. However, research efforts made in BIM for sustainable building management, especially using in all four Integrated Digital Delivery (IDD) phases are minimal. Therefore, this study features a combined scientometric analysis and IDD thematic discussion examining 471 scholarly bibliographies accessed from the Web of Science (WoS) database. The purpose of this study is to statistically classify BIM-sustainability publications from 2007 to 2019 in order to understand the research status, key themes, trends, and future challenges to be addressed in the field of sustainable BIM. The most influential scholars, institutes, regions/countries, articles, and journals have been identified. Moreover, clustering analyses identified topics that sustainable BIM research tended to gravitate toward, such as cloud approaches, data sharing, life cycle energy efficiency, and informetric analysis. The top 100 most cited documents from WoS were also manually classified into four quadrants of IDD, namely design, fabrication, construction, and asset delivery and management. Ten BIM-sustainability phenomena were observed throughout the life cycle of IDD. Finally, key research gaps and important areas for future research in this field were identified. The clearly delineated clusters and themes provide a practical overview and a deeper understanding of the current research progress of IDD for building sustainability, highlighting the challenges and research gaps for future research.
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1. Introduction

In recent years, digital transformation and sustainability have received growing attention in both academia and the Architectural, Engineering and Construction (AEC) industry. Building information modeling (BIM), virtual design and construction (VDC), and integrated digital delivery (IDD) are core technologies in this domain. Building Information Modeling (BIM) provides an integrated, interactive, and virtual approach to underpin building design, construction and operation, it also provides intuitive feasibility studies to support green building design, such as using BIM models as the primary source to achieve LEED and leveraging on BIM model as basis of energy model (Eastman et al, 2008, 2011). With the widespread adoption of BIM in the AEC industry, 6D BIM specifically has attracted the interest of researchers in various specialties. It is generally believed that 6D is 5D + sustainability, which is mainly used for energy performance analysis, environmental assessment, and life cycle assessment (LCA). The adoption of 6D BIM has demonstrated various benefits in the design, construction, and operation and management phases. In the early design stage, the application of 6D BIM enables more accurate energy estimation. During the construction process, the estimated future energy consumption can be continuously monitored and optimized, which essential for ensuring that the overall energy consumption of the construction process and the future operation stage can be reduced and made more environmentally friendly. An integrated 6D-BIM framework was developed for the automatic assessment of building sustainability performance (Yung and Wang, 2014). Application of 6D BIM in operation and facility management (O&FM) is another more recently emerging topic of research. Though in view of existing guidelines, articles, and reports relevant to BIM-O&M, Gao and Pishdad-bozorgi (2019) contend that more research is needed on the return on investment of innovative systems to demonstrate the value of BIM-O&M applications, and that improved life-cycle cost analysis methods are key to demonstrating this value.

The Center for Integrated Facility Engineering (CIFE) at Stanford University provides a classical definition of Virtual Design and Construction (VDC) as "the use of integrated multi-disciplinary performance models of design-construction projects to support explicit and business objectives" (Kunz and Fischer, 2020). Integrated Digital Delivery (IDD) refers to the digital integration of work processes and stakeholders throughout the construction and building life-cycle, which includes design, fabrication, and assembly on-site, as well as the asset delivery and management phase (Building and Construction Authority of Singapore, 2020). As represented by the yellow inner circle in Fig. 1, BIM is pitched to be at the core of design, fabrication, construction, asset delivery and management, and. VDC occupies the second layer, which covers the design and construction phases, while IDD circles around as the outermost layer, encompassing the full life cycle of the building. BIM is typically a specific modeling process to meet a specific purpose, such as creating a model for regulatory authorities' approval or creating a model for Quantity Take-Off (QTO). VDC leverages BIM models to facilitate communication during the design and construction phases, so as to achieve explicit project or organizational goals and to improve performance. IDD in turn takes BIM as its core while spanning the entire life cycle, from design, construction, and fabrication to asset delivery and management. In short, BIM is the core of VDC and IDD, and all these three components cover different phases. Recent studies have demonstrated that the adoption and implementation of BIM, VDC, and IDD contributes measurable value to organizations (Gurevich and Sacks, 2020). However, Shirowzhan et al. (2020) reviewed 57 articles on BIM Compatibility (BIM-COM) using bibliographic analysis

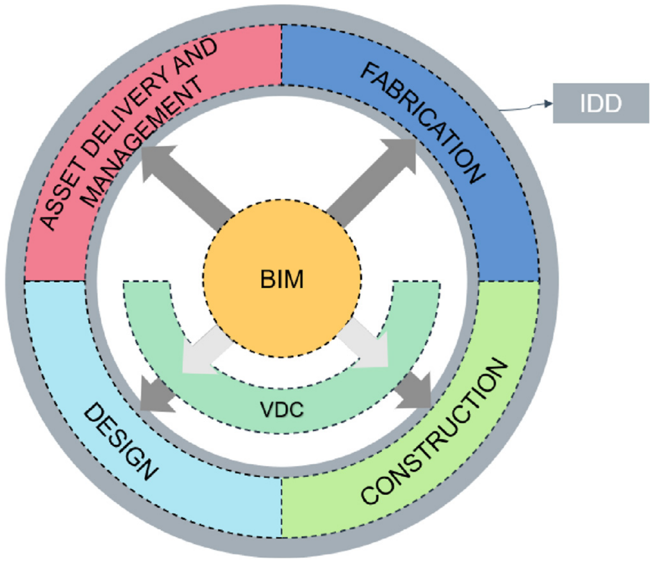

Fig. 1. Transition from BIM-VDC-IDD.

techniques and found that interoperability remains an important obstacle to the application of BIM. Hwang et al. (2020) conducted a survey structured around 32 key IDD solutions drawn from their literature review to examine IDD implementation and its perceived improvement of project performance. Their results, supplemented by follow-up interviews, indicated that 38.71% of organizations implemented digital technologies in all four quadrants of IDD. In addition, most participants agreed that the IDD implementation improved project performance as measured by cost, quality, or schedule.

As sustainable building and BIM-VDC-IDD continuously gain momentum, a comprehensive and systematic review is needed to capture the current status on research investigating the application of BIM-sustainability throughout the IDD life cycle, as well as to understand related emerging trends. Therefore, this study explores IDD for sustainability from a global perspective. Various review-based studies have been conducted to survey BIM-sustainability efforts and experiences (Ansah et al., 2019; Lu et al., 2017; Wong and Zhou, 2015). Through a systematic review of 36 BIM standards and guidelines and 91 academic publications, Chong et al. (2017) identified four areas in BIM development that needs to addressed: (1) new BIM solutions for sustainability assessment, (2) interoperability challenges among BIM authoring tools and Building Performance Analysis (BPA), (3) innovative procurement approaches to incorporate social sustainability into projects, and (4) the streamlining of BIM for renovation and demolition.

While sustainable BIM applications have been critically reviewed, academic interest in BIM-sustainability has grown over the last decade as decision makers have been devoting greater attention to building lifecycle performance towards cradle-to-cradle lifecycle design, construction, and facility operation (Gan et al., 2020). IDD is positioned to perform a central role in such integration. The above-mentioned review-based studies provide a number of valuable insights on BIM-sustainability and IDD, but they are primarily qualitative in approach. In comparison, the present study adopted a combined scientometric review and IDD thematic approach to quantitatively and qualitatively review 471 articles pertaining to BIM and sustainability published between 2007 and 2019. The reviewed article types include conference papers and international peer-reviewed journals. The present study is believed to be the first ever attempt to survey sustainability research through the lens of the IDD quadrants. A critical review applying these methodologies can contribute to systematically identifying gaps in existing research and highlighting future trends and research challenges.

The rest of the paper is organized as follows. Section 2 outlines the research design of this review. Section 3 presents general statistics regarding the number and kind of articles published on BIM and sustainability. Section 4 presents the results of our scientometric analysis, specifically co-author, co-word, and co-citation analyses. Section 5 is a thematic discussion guided according to the four quadrants of IDD. Section 6 features a co-citation clustering analysis along with a detailed overview of knowledge gaps and potential future research directions. Section 7 recaps the contributions of the present study followed by Section 8 providing a summary of key takeaways.

2. Research methodology

Scientometric analysis was used to quantitatively analyze patterns in the scientific literature and to provide a deeper understanding of the knowledge structure and emerging trends in a research field (Chen et al., 2012). Fig. 2 illustrates the research protocol for reviewing, building upon schemas developed and applied by Liu et al. (2019); Vilutiene et al. (2019); Zhang and Yuan (2019); and Zhao (2017). In Stage 1, a preliminary search was conducted, followed by double-check screening and data pre-processing. Next in stage 2, the bibliographic data were used to establish the networks in scientometric analysis at stage 2. In order to facilitate the thematic discussion in Stage 3, the top 100 most cited documents were manually classified into the four quadrants of IDD.

2.1. Knowledge discovery approach

Knowledge discovery is a visualization process that describes the relationship among entities with graph models. It can be used to reveal the potential linkages among entities of a core issue, as well as their nature. Thus, it allows the illustration of the stereoscopic data space of a specific issue from a new perspective. This approach can also improve the understanding of a research topic from readers and industry practitioners by endowing better explanatory power of the relationship among subjects. Scientometric analysis represents one common method of knowledge discovery. Scholars have used different types of scientometric toolkits, including Citespace, VOSviewer, VantagePoint, and Gephi to analyze, map, and visualize bibliometric data (Hu et al., 2019; Kim et al., 2016; Yevide et al., 2016; Zhang and Yuan, 2019). CiteSpace is a type of scientific and technological text mining and visualized analysis software based on citation analysis theory (Chen, 2016). Citespace was used in this study to draw the knowledge map of development in the field of science to intuitively display the information panorama and macroscopic structure of the scientific knowledge field as well as trends in how a certain subject or knowledge field was treated during a certain period of time (Chen, 2016). CiteSpace can also be used to detect and discover the evolution of some pioneering research fields and the corresponding important theoretical literature. In addition, the unique time zone view and citation burst detection functions of CiteSpace can aid in the discovery of the hotspots and fronts of research in a given field of science.

2.2. Data collection

2.2.1. Preliminary search

The purpose of the preliminary search was to identify the

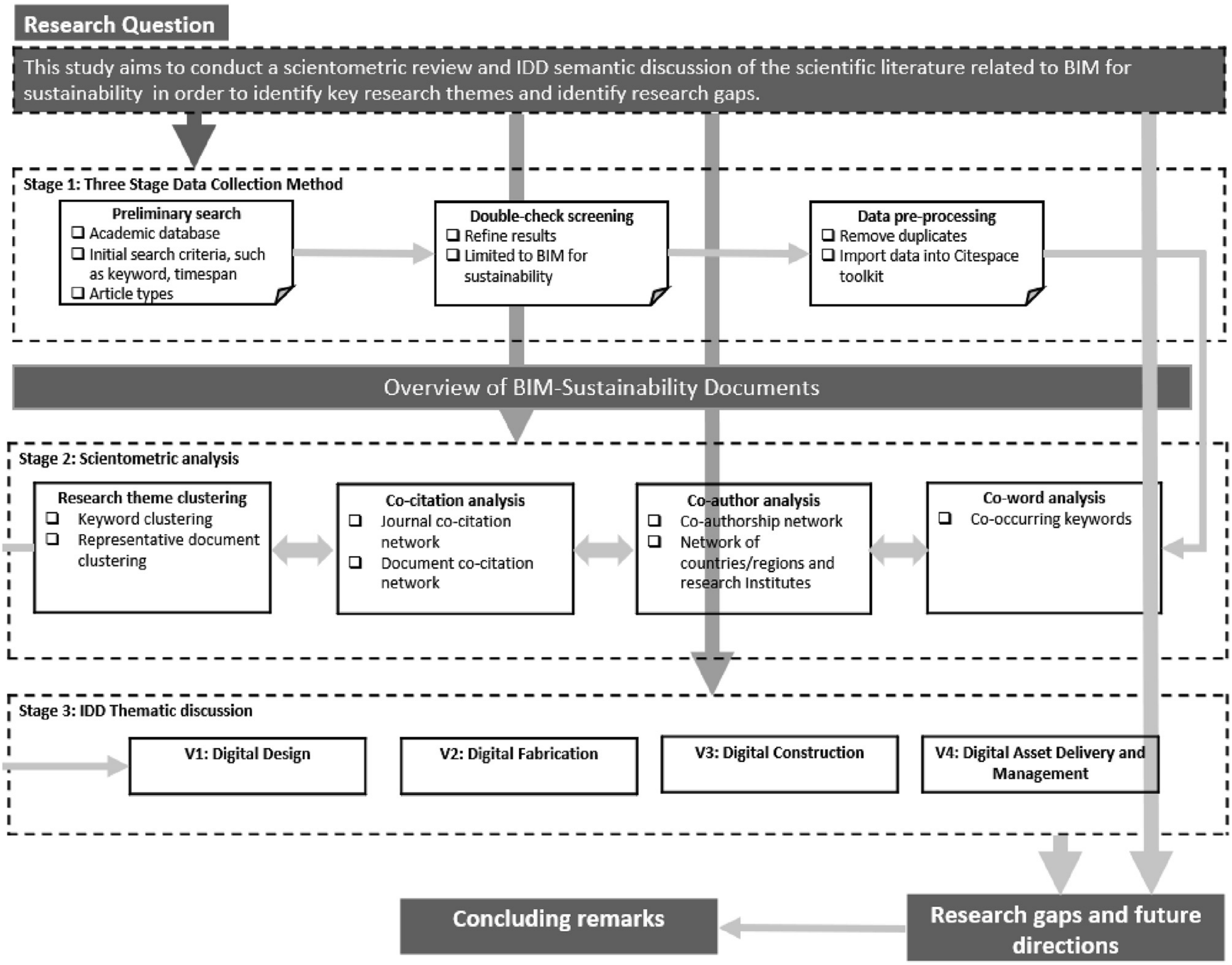

Fig. 2. Systematic protocol for reviewing BIM-sustainability research.

research boundary. We began this search by identifying the relevant list of academic databases. In this step, the Web of Science (WoS) database was selected, because WoS is one of the most comprehensive databases, covering over 12,000 influential journals and 150,000 conference proceedings (Clarivate Analytics, 2020). It encompasses the majority of published, peer-reviewed articles in the AEC industry. Next, the initial search criteria were defined. The initial search keywords in WoS included “Building Information Model” or “Building information Modeling” or “Building Information Modeling”, restricted to the “Title” field, to retrieve BIM-related bibliographic data. Double quotation marks “” represent precise phrase search. In order to prevent in advertently omitting target literature, the search timespan was set as “All year (1990–2019)”. The retrieval was conducted on October 11, 2019. A total of 3641 documents were retrieved from the preliminary search.

2.2.2. Double-check screening

In order to ensure the comprehensiveness and reliability of the bibliographic data, the document types were only limited to article, proceeding papers, review, and early access, while excluding book review, news items, and editorial material. As similarly applied by other researchers (He et al., 2017; Toledo et al., 2019), a secondary refining search of the 3641 BIM documents was conducted using keyword “Green” or “Sustainable” or “Sustainability”. A total of 471 BIM-sustainability documents were retrieved. The retrieval procedure is detailed in Table 1.

2.2.3. Data pre-processing

Duplicate bibliographic data should be removed prior to scientometric analysis Liu et al. (2019). After data pre-processing to remove this redundant data, 471 documents related to BIM-sustainability were imported into Citespace for analysis.

3. Statistical overview of documents related to BIM-sustainability

Fig. 3 shows the distribution of the selected papers from 2007 to 2019. The results indicate that the number of publications grows significantly from 2014 onward, comprising over 80% of the total (i.e., 387 out of 471). More specifically, 251 documents (53% of the total) have been published in the past three years. It is worth noting that 97 papers were published in 2019, accounting for more than 20% of total publications. It can be observed that BIM-sustainability research was initiated in 2007. Zeng and Tan (2007) explored BIM-based intelligent parametric modeling with the aim of advancing information organization and sustainable development in the building industry.

Table 2 lists 17 Journals in which more than 5 papers related to BIM-sustainability with an H-index have been published. Of these,

Table 1
Detailed retrieve process.

Stages	String and Filter	No of Document Retrieved
Preliminary Search	Database: Web of Science (Core Collection)	3641
	Topic: "Building Information Model" OR "Building Information Modeling" OR "Building Information Modeling"	
	Timespan: All year (1990–2019)	
Double Screen Check	Document types only limited to article, proceeding papers, review and early access, excluding book review, news items and editorial material	3592
	Refine results "Green" OR "Sustainable" OR "sustainability"	472
Data pre-processing	Remove duplicates	471

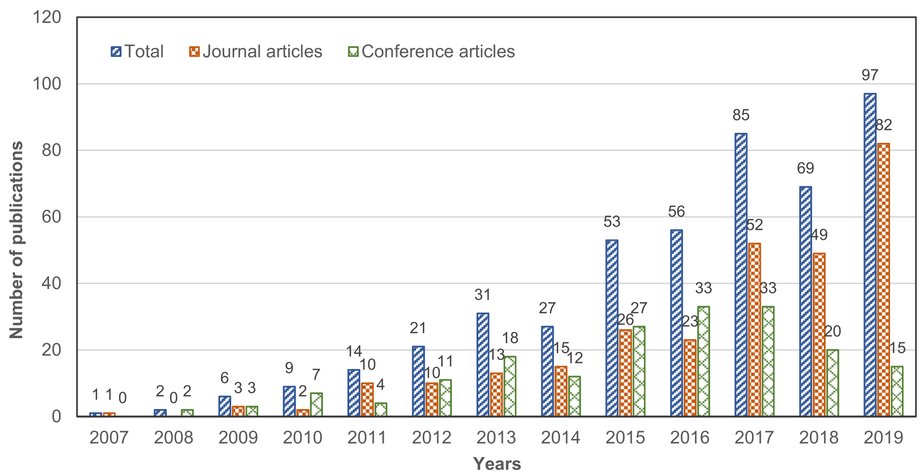

Fig. 3. Distribution of the documents published from 2007 to 2019.

Table 2
Top productive journals.

Source publications	Host Country	Count	Percentage	H-index[a]
Regular Journals		***149***	***31.6%***	
Automation in Construction	Netherlands	28	5.9%	95
Sustainability	Switzerland	25	5.3%	53
Journal of Cleaner Production	Netherlands	23	4.9%	150
Journal of Information Technology in Construction	Sweden	19	4.0%	38
Engineering and Construction and Architectural Management	United Kingdom	9	1.9%	49
Energy and Buildings	Netherlands	7	1.5%	147
Facilities	United Kingdom	6	1.3%	38
Journal of Building Engineering	Netherlands	6	1.3%	18
Journal of Construction Engineering and Management	United States	6	1.3%	95
Building and Environment	United Kingdom	5	1.1%	124
Buildings	Switzerland	5	1.1%	NA[b]
Journal of Green Building	United States	5	1.1%	17
Sustainable Cities and Society	Netherlands	5	1.1%	34
Journal of Professional Issues in Engineering Education and Practice	United States	5	1.1%	33
Others (<5 papers)		137	29.1%	
Conference Proceedings		***40***	***8.5%***	
Procedia Engineering	Netherlands	25	5.3%	51
ICSDEC 2016 Integrated Data Science Construction and Sustainability – Procedia Engineering	Netherlands	9	1.9%	NA[b]
Winter Simulation Conference Proceedings	United States	6	1.3%	58

[a] H-index obtained from Scimago Journal & Country Rank [(Scimago Lab, 2019)].
[b] NA: Not available.

14 regular journals contributed 149 publications, thus accounting for 31.6% of the total amount. The other 3 conference-oriented journals contributed 40 documents, or 8.5% of all publications. With regard to the 149 journal articles, *Automation in Construction* published 28 papers (5.9%), ranking first. This journal is followed by *Sustainability* with 25 publications (5.3%) and *the Journal of Cleaner Production* with 23 publications (4.9%).

Table 3 lists the top 10 most cited articles. The citation statistics were obtained from the WoS Core Collection. The top three most cited documents are Azhar et al. (2011), Basbagill et al. (2013), and Wong and Zhou (2015).

Table 3
Top 10 highly cited documents.

SN	Author and year	Article Type	Article Title	Journal	Times cited
1	Azhar et al. (2011)	Article	Building information modeling for sustainable design and LEED at rating analysis.	Automation in Construction	182
2	Basbagill et al. (2013)	Article	Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts	Building and Environment	176
3	Wong and Zhou (2015)	Review	Enhancing environmental sustainability over building life cycles through green BIM: A review	Automation in Construction	115
4	Cheng and Ma (2013)	Review	A BIM-based system for demolition and renovation waste estimation and planning	Waste Management	87
5	Wong and Fan (2013)	Article	Building information modeling (BIM) for sustainable building design	Facilities	85
6	Sebastian (2011)	Review	Changing roles of the clients, architects and contractors through BIM	Engineering Construction and Architectural Management	85
7	Bynum et al. (2013)	Article	Building information modeling in support of sustainable design and construction	Journal of Construction Engineering and Management	79
8	Becerik-Gerber et al. (2011)	Article	The pace of technological innovation in architecture, engineering, and construction education: Integrating recent trends into the curricula	Journal of Information Technology in Construction	71
9	Becerik-Gerber and Kensek (2010)	Article	Building information modeling in architecture, engineering, and construction: Emerging research directions and trends	Journal of Professional Issues in Engineering Education and Practice	55
10	Nawari (2012)	Article	BIM standard in off-site construction.	Journal of Architectural Engineering	53

4. Scientometric analysis

In our scientometric analysis, Citespace was used to construct various networks based on the 471 bibliographic data obtained from WoS. First, the time-slicing range included 2007 to 2019, with each year selected as a time slice. The threshold of a time slice was 50, which means the top 50 most cited or occurred items were extracted for the analysis. Then the Cosine algorithm was used to calculate the correlation strength of nodes in the network. Following this, the pathfinder (a function of Citespace software) removes redundant links for network pruning (Chen and Morris, 2003). Finally, the corresponding node types were selected with corresponding scientific knowledge network drawn. The following sections describe the co-author analysis (Section 4.1), co-word analysis (Section 4.2), co-citation analysis (Section 4.3).

The following two key indicators are commonly used in scientometric analysis to measure the importance of each node:

- The betweenness centrality is defined as the ratio of the shortest path between two nodes to the sum of all these shortest paths (Freeman, 2014). Nodes in Citespace with high betweenness centrality often play an important role in connecting two or more large groups (Zhao, 2017). These nodes are highlighted with a purple ring in Citespace.
- Citation burst detection in Citespace uses Kleinberg's algorithm (Kleinberg, 2003) and hierarchical structure to indicate when there is a dramatic change in the frequency of a datum over time (He et al., 2017). A citation burst indicates that a node attracted great attention from the research community at a certain time (Zhao, 2017). The nodes with high citation burst are represented by red.

4.1. Co-author analysis

4.1.1. Author co-citation network

As shown in Fig. 4, an author co-citation network was established to distinguish relationships between various authors. This network contains 337 nodes and 1152 links. Each node in Fig. 4 refers to one author, and every link between the authors stands for an established collaboration. Fig. 4 does not focus on BIM publications generally, but only on scientometrics analysis of sustainability and green buildings in BIM publications. The node size stands for the number of published BIM-sustainability articles with high influential of each author while the thickness of the links refers to the strength of a partnership during a specific year. The node size represents the strength of the citation burst for the author. It can be observed from Fig. 4 that authors like Salman Azhar, Johnny Wong, and Wei Wu generated stronger citation bursts, with representative articles including Azhar et al. (2011), Wong and Zhou (2015) and Wu and Issa (2010).

The top 10 most cited authors were identified from the author co-citation network, namely: Salman Azhar (frequency = 142, United States), Charles Eastman (frequency = 133, United States), Johnny Kwok-Wai Wong (frequency = 63, Australia), Eddy Krygiel (frequency = 63), Bilal Succar (frequency = 53, Australia), Farzad Jalaei (frequency = 49, Canada), Rebekka Volk (frequency = 47, Germany), Arno Schlueter (frequency = 47, Switzerland), Burcin Becerik-Gerber (frequency = 47, United States), and Rafael Sacks (frequency = 46, Israel). There is a subordinate diversity among authors, which further indicates the development of BIM-sustainability research.

In addition, scholars with high betweenness centrality were also distinguished with purple trims. Representative authors with centrality of more than 2.0 include Ignacio Zabalza Bribián (centrality = 0.24), Sumedha Kumar (centrality = 0.24), Vladimir Bazjanac (centrality = 0.21), and Endong Wang (centrality = 0.20), who are the main intellectual driving forces in this research field and play an important role in interconnecting with the work of various research groups.

Moreover, 18 scholars have received citation bursts, and the frequency of citations increased sharply in a short period of time. These authors include Eddy Krygiel (strength = 4.90, 2012–2014), Johnny Kwok-Wai Wong (strength = 4.21, 2017–2019), Sandeep Kota (strength = 3.88, 2017–2019), Peter ED Love (Strength = 3.60, 2017–2019), Ebrahim P. Karan (strength = 3.56, 2016–2017), Tajin Biswas (strength = 3.47, 2011–2016), AIA (strength = 3.29, 2015–2016) and so on. The articles, books, and documents published by these scholars or association have been deemed noteworthy by other scholars in the field, and their work has influenced the development of BIM-sustainability research globally.

An analysis of author productivity (see Table 4) reveals that Daniel W.M. Chan (The Hong Kong Polytechnic University) and Jack C.P. Cheng (The Hong Kong University of Science and Technology)

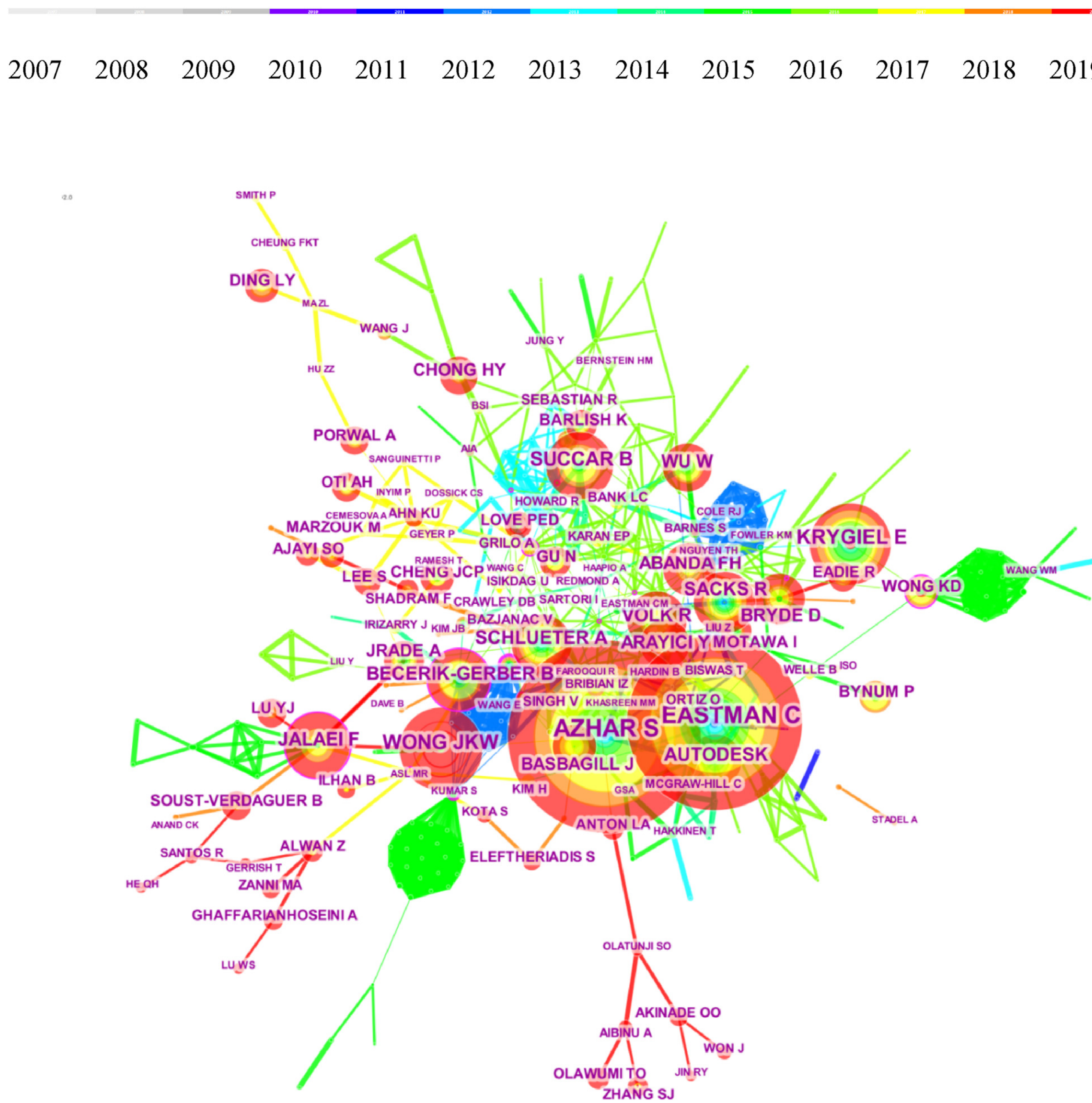

Fig. 4. Author co-citation network.

Table 4
Top 9 most productive authors according to h-Index.

Authors	Research Institution	Country/Regions	Counts	h-Index [a]
Daniel W.M. Chan	The Hong Kong Polytechnic University	China	10	51
Xiangyu Wang	Curtin University	Australia	7	44
Jack C.P. Cheng	The Hong Kong University of Science and Technology	China	9	28
Mohamed Marzouk	Cairo University	Egypt	6	26
John Tookey	Auckland University of Technology	New Zealand	5	21
Ali Ghaffarianhoseini	Auckland University of Technology	New Zealand	5	19
Ruoyu Jin	University of Brighton	United Kingdom	5	15
Wei Wu	California State University	United States	7	13
Timothy O.Olawumi	The Hong Kong Polytechnic University	China	7	10

[a] The authors' H-index are obtained from Google Scholar.

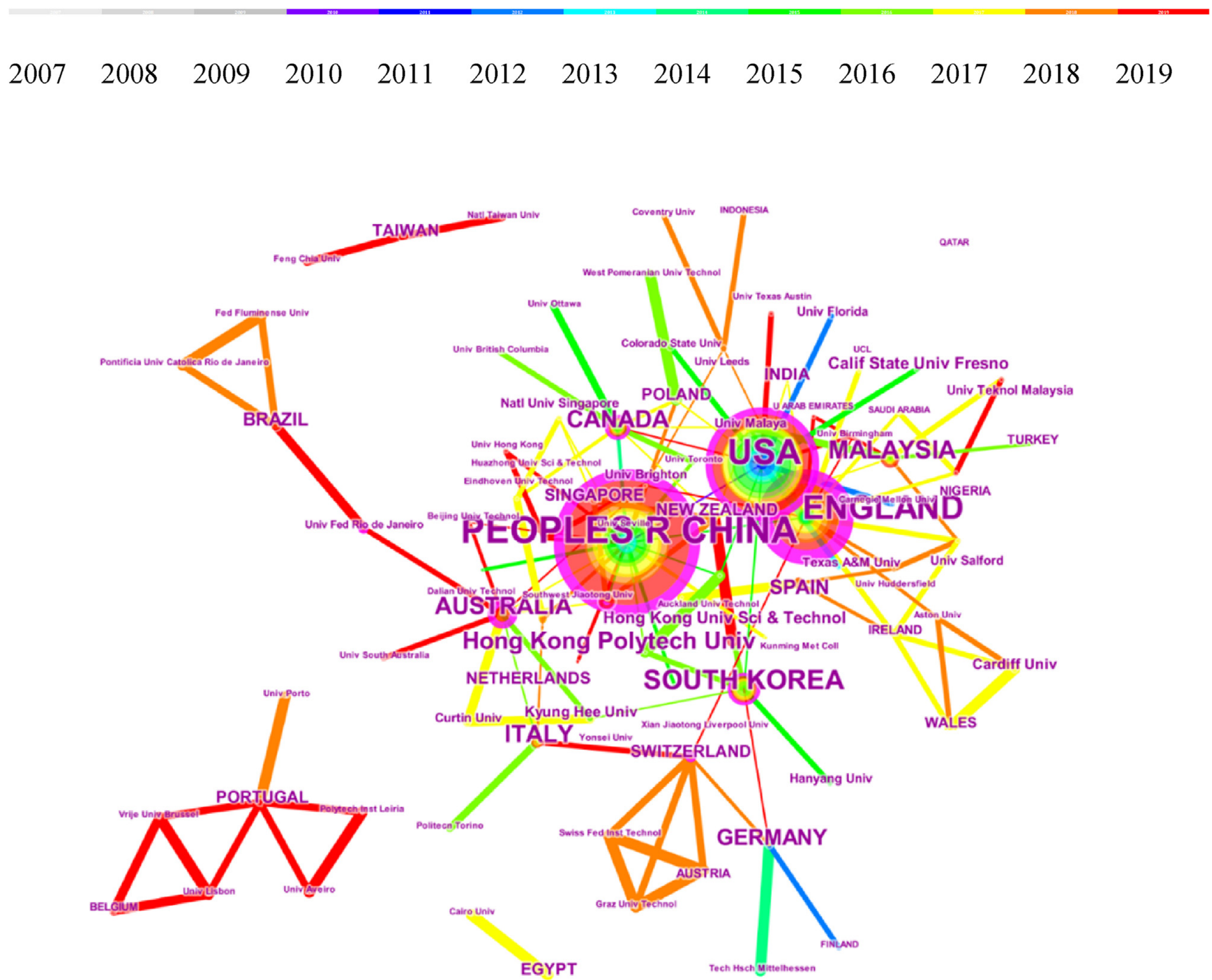

Fig. 5. Co-authorship countries/regions and research institutes network.

were two of the most productive researchers in the field of BIM-sustainability. Timothy O. Olawumi (The Hong Kong Polytechnic University), Xiangyu Wang (Curtin University), and Wei Wu (California State University) tied for third place with 7 published articles each.

4.1.2. Network of co-authors' countries/regions and research institutes

A network of countries/regions and institutes was generated to explore their contributions to the body of knowledge in this field. There are 86 nodes and 130 links in the following network. Fig. 5 depicts these connections, revealing that the top 3 countries/regions most productive in the research field of BIM-sustainability are China (98 articles), the USA (86 articles), and England (59 articles).

South Korea and Germany are connected by a red line, indicating collaboration between researchers from the two countries in 2019. In addition, authors from countries such as England and China have strong international collaborations. In terms of research institute contributions, research on BIM-sustainability has made significant progress at the following institutes: The Hong Kong Polytechnic University (16 articles), and The Hong Kong University of Science and Technology (6 articles), and California State University (6 articles).

Table 5
High-frequency and high-centrality keyword of BIM for sustainability research during 2007–2019.

SN	Keyword with High Frequency		Keyword with High Centrality	
	Keyword Name	Frequency	Keyword Name	Centrality
1	Sustainability	83	Interoperability	0.31
2	Design	75	Life Cycle Assessment	0.14
3	Construction	57	Energy	0.14
4	Life Cycle Assessment	56	Construction Project	0.14
5	Performance	50	Simulation	0.14
6	Framework	45	Environment Impact	0.13
7	System	37	Green BIM	0.12
8	Green Building	34	Framework	0.11
9	Energy	33	Implementation	0.11

Furthermore, nodes with high betweenness centrality are identified with purple outer rings, as shown in Fig. 5. The most prominent countries/regions were England (centrality = 0.61), China (centrality = 0.52), the USA (centrality = 0.34), Australia (centrality = 0.27), and Switzerland (centrality = 0.20). For research institutes, California State University (centrality = 0.12), and University of Leeds (centrality = 0.09) achieved particularly high scores. The countries and institutes of these nodes with high

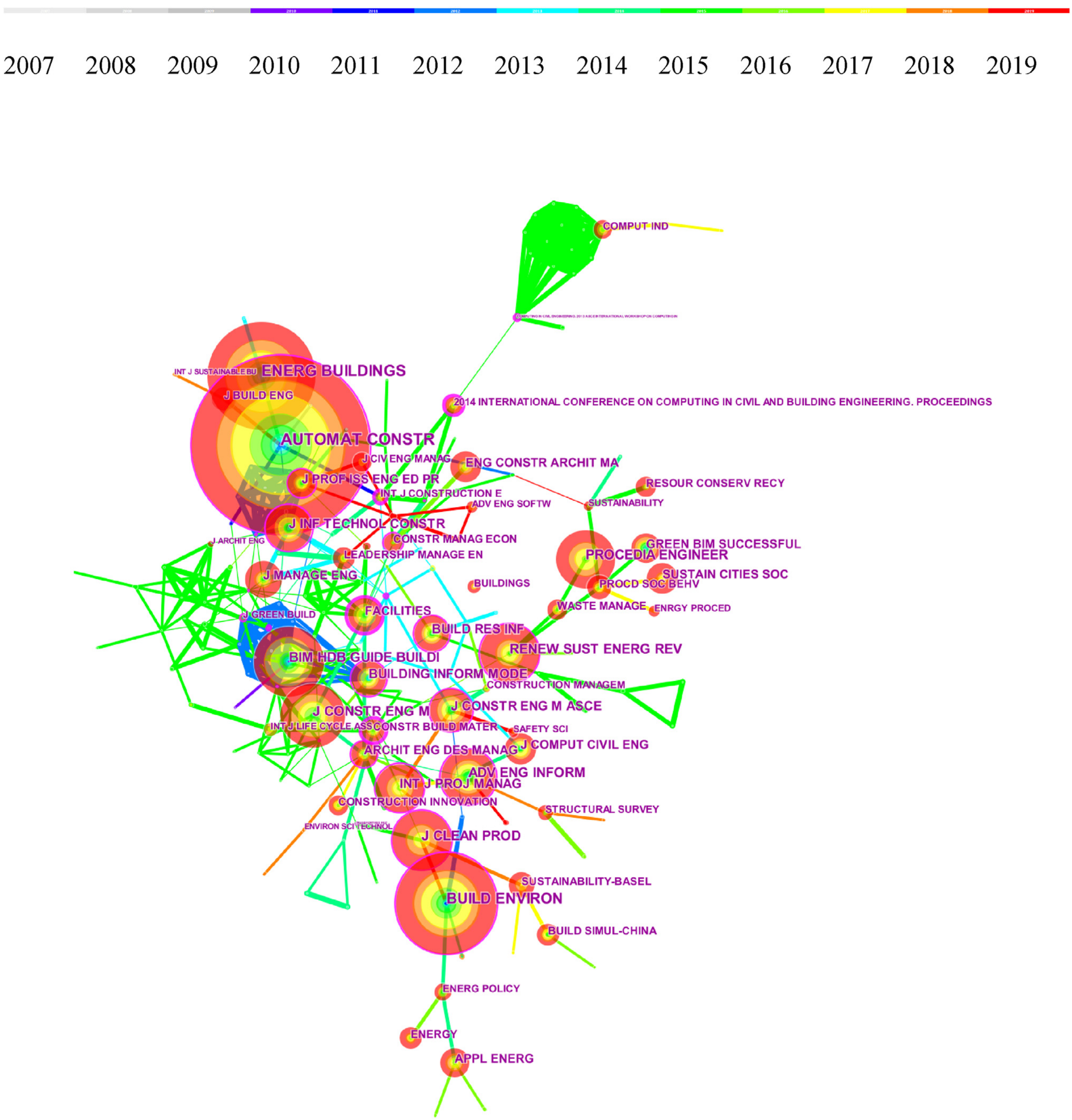

Fig. 6. Journal co-citation network.

betweenness centrality have played a particularly critical role in advancing BIM-sustainability research.

Moreover, three countries have received citation bursts, indicated by red internal rings in Fig. 5, varying in strength during different periods of time: USA (strength = 15.80, 2009–2014), Canada (strength = 4.43, 2014–2016) and South Korea (strength = 3.25, 2015–2016). At the research institute level, California State University is salient (strength = 2.83, 2015–2016). There are also some regions/countries in the network do not have any collaboration links with others, such as Egypt, Taiwan, Qatar, and Portugal. These countries/regions are far away from the main network in the research areas and may consider adjusting their research policies to promote more collaboration with members of this network.

4.2. Co-word analysis

The nodes that scored high in centrality are also illustrated in Table 5. Interoperability and life cycle assessment have attracted increased academic interest as IDD requires a high level of system integration among different industry practitioners throughout the life cycle of buildings. How to achieve smooth, unimpeded information flow from early design, to fabrication, and then to construction and asset management has thus become a topic of primary importance.

The keywords with high betweenness centrality have a crucial role in the research field of BIM-sustainability and in connecting the main branches of knowledge. Citation frequency of the following three key words has also increased dramatically: “BIM”

Table 6
Journal with citation bursts.

Journals	Burst Strength	Time span
The International Journal of Life Cycle Assessment	5.24	2017–2019
Automation in Construction	4.47	2009–2011
International Journal of Sustainable Built Environment	3.32	2017–2019
Solar Energy	3.06	2013–2015
Journal of Environment and Management	3.03	2015–2017

(burst strength = 22.64, 2008–2014), “green building” (burst strength = 4.97, 2012–2015) and “sustainable design” (burst strength = 3.17, 2010–2013), reflecting that these keywords indicate the focus of research in corresponding years.

4.3. Co-citation analysis

4.3.1. Journal co-citation network

The journal co-citation network in the research area of BIM-sustainability was established based on the 471 bibliographic data items. The network consists of 181 nodes and 664 links.

As shown in Fig. 6, in terms of the co-citation frequency of journals, the five most influential journals were *Automation in Construction* (frequency = 288), *Energy and Buildings* (frequency = 177), *Building and Environment* (frequency = 162), *the BIM Handbook* (frequency = 120) and *Journal Construction Engineering and Management* (Frequency = 104). These journals have made important contributions to BIM-sustainability research and are cited more

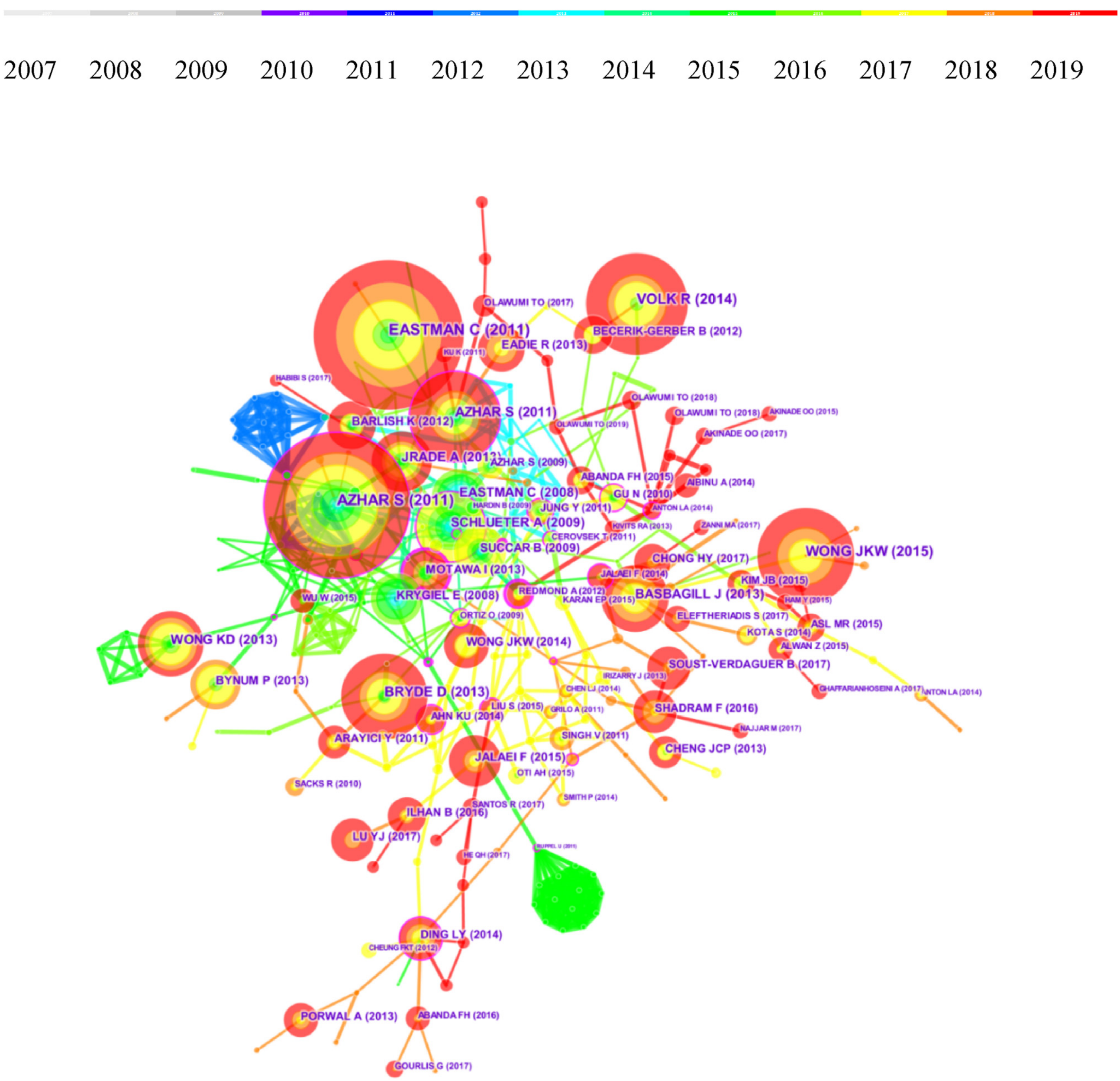

Fig. 7. Document co-citation network.

Table 7
Top 23 cited articles based on WoS citation metric.

SN	Author and year	Article title	Name of Journals/books	Citations
1	Eastman et al. (2011)	BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors	BIM Handbook	69
2	Azhar et al. (2011)	Building information modeling for sustainable design and LEED ® rating analysis	Automation in Construction	66
3	Volk et al. (2014)	Building Information Modeling (BIM) for existing buildings - Literature review and future needs	Automation in Construction	47
4	Wong and Zhou (2015)	Enhancing environmental sustainability over building life cycles through green BIM: A review	Automation in Construction	44
5	Azhar (2011)	Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry	Leadership and Management in Engineering	42
6	Bryde et al. (2013)	The project benefits of building information modeling (BIM)	International Journal of Project Management	40
7	Basbagill et al. (2013)	Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts	Building and Environment	32
8	Schlueter and Thesseling (2009)	Building information model based energy/exergy performance assessment in early design stages	Automation in Construction	32
9	Wong and Fan (2013)	Building information modeling (BIM) for sustainable building design	Facilities	31
10	Jrade and Jalaei (2013)	Integrating building information modeling with sustainability to design building projects at the conceptual stage	Building Simulation	29
11	Eastman et al. (2008)	BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors	BIM Handbook	27
12	Krygiel (2008)	Green BIM: Successful Sustainable Design with Building Information Modeling	Green BIM: Successful sustainable design with BIM	25
13	Succar (2009)	Building information modeling framework: A research and delivery foundation for industry stakeholders.	Automation in Construction	25
14	Jalaei and Jrade (2015)	Integrating building information modeling (BIM) and LEED system at the conceptual design stage of sustainable buildings	Sustainable Cities and Society	25
15	Barlish and Sullivan (2012)	How to measure the benefits of BIM - A case study approach	Automation in Construction	24
16	Bynum et al. (2013)	Building information modeling in support of sustainable design and construction	Journal of Construction Engineering and Management	24
17	Wong and Kuan (2014)	Implementing "BEAM Plus" for BIM-based sustainability analysis	Automation in Construction	22
18	(Motawa and Carter, 2013)	Sustainable BIM-based evaluation of buildings	Procedia Social and Behavioral Sciences	22
19	Eadie et al. (2013)	BIM implementation throughout the UK construction project lifecycle: An analysis	Automation in Construction	21
20	Lu et al. (2017)	Building Information Modeling (BIM) for green buildings: A critical review and future directions	Automation in Construction	20
21	Shadram et al. (2016)	An integrated BIM-based framework for minimizing embodied energy during building design	Energy and Building	20
22	Ding et al. (2014)	Building Information Modeling (BIM) application framework: The process of expanding from 3D to computable nD	Automation in Construction	20
23	Soust-Verdaguer et al. (2017)	Critical review of bim-based LCA method to buildings	Energy and Building	20

often by scholars in this field.

As shown in Fig. 6, some nodes with high betweenness centrality are highlighted with purple rings, such as *2014 International Conference on Computing in Civil and Building Engineering* (centra lity = 0.32), *Computing in Civil Engineering 2013*) (centrality = 0.30), *Construction and Building Material* (centrality = 0.29), *International Journal of Construction Education and Research* (centrality = 0.27), *International Journal of Low Energy and Sustainable Buildings* (centrality = 0.22) and *Facilities* (centrality = 0.20). These journals represent crucial academic hubs in the research area at various stages Liu et al. (2019).

In addition, 14 cited journals received citation bursts, out of which 5 journals received citation bursts of 3.0 and above, as shown in Table 6. This demonstrates that articles published in these journals were widely cited in a short period of time and deserve particular attention.

4.3.2. Document co-citation network

Document co-citation analysis is used to measure bibliographic records and help understand the intellectual structures of a given knowledge domain. The document co-citation network for our analysis is shown in Fig. 7, with 249 nodes and 536 links. Based on the citation records obtained from the network, there were 23 documents cited more than 20 times, as shown in Table 7.

Meanwhile, documents with high betweenness centrality scores are indicated with purple trim in the network. Representative documents include Redmond et al. (2012), Azhar et al. (2012), Ding (2008) and Motawa and Carter (2013). These documents constitute the basic foundation of BIM-sustainability research.

A number of articles have received especially strong citation bursts, among which include: Eastman et al. (2011), Burst strength = 11.15, Time span: 2010–2016; Krygiel (2008), Burst Strength = 10.39, Time span: 2012–2016; Schlueter and Thesseling (2009), Burst Strength = 6.15, Time span: 2010–2016; and Succar (2009), Burst Strength = 5.00, Time span: 2013–2017. These citation bursts indicate that the direction of BIM-sustainability research in the AEC industry tended to be influenced by the cited documents in a specific period.

5. Thematic discussion of integrated digital delivery (IDD) quadrants

As defined by the Building and Construction Authority of Singapore, Integrated Digital Delivery (IDD) *refers to* "the use of digital technologies to integrate work processes and connect stakeholders working on the same project throughout the construction and building life cycle" (BCA, 2019a). For the purpose of facilitating our thematic discussion on research priorities, the top

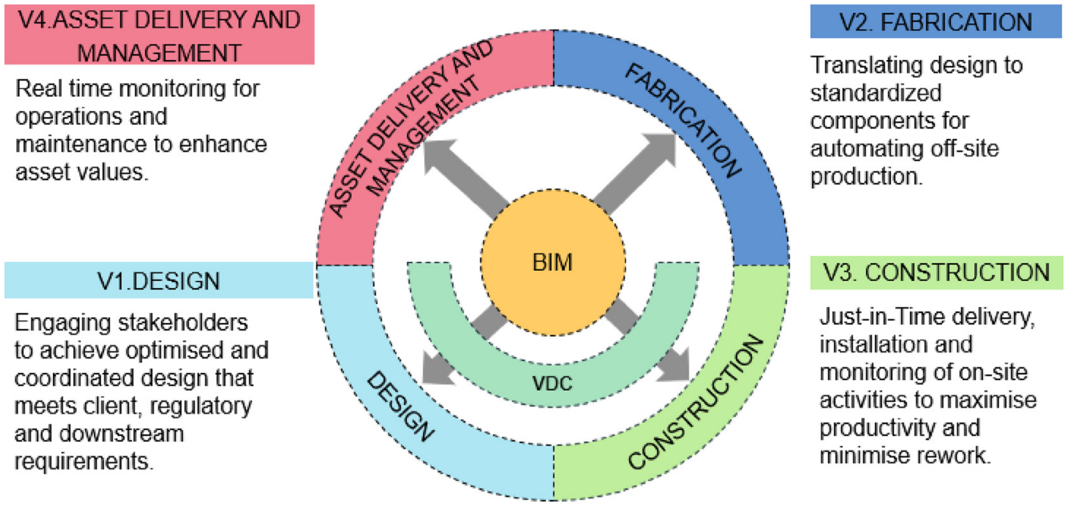

Fig. 8. Scope of integrated digital delivery (BCA, 2019a).

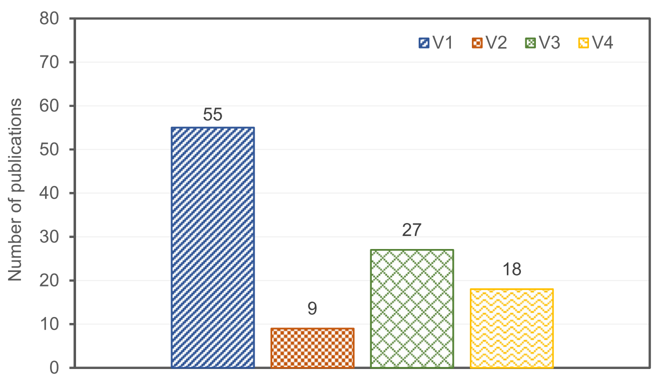

Fig. 9. IDD-based categorization of BIM-sustainability research from 2007 to 2019.

100 most cited documents were divided into one of the quadrants of Integrated Digital Delivery (IDD), namely Digital Design (V1), Digital Fabrication (V2), Digital Construction (V3), or Digital Asset Delivery and Management (V4), as illustrated in Fig. 8.

It can be observed from Fig. 9 that most BIM-sustainability publications have concentrated on digital design (V1), digital construction (V3) and digital asset delivery and management (V4). Relatively few publications have focused on digital fabrication (V2). Fig. 10 provides the conclusive observations of BIM-sustainability throughout the life cycle of IDD, further detailed in Sections 5.1 to 5.4.

5.1. Vertical 1: digital design

After systematically reviewing the top 100 most cited articles related to BIM-sustainability, the following observations were made in the digital design stage:

5.1.1. Supports green building assessment (GBA) and certification

Of all green building assessment criteria, LEED was the most frequently mentioned (Azhar et al., 2011; Chen et al., 2012; Chen and Nguyen, 2015; Jalaei and Jrade, 2015; Jrade and Jalaei, 2013; Wong and Fan, 2013; Wu and Issa, 2012, 2014). BEAM Plus (Wong and Kuan, 2014) and BREEAM (Ilhan and Yaman, 2016; Zanni et al., 2014) were rarely evaluated in the literature. The high incidence of LEED may be closely related to its widespread use in countries around the world. Azhar et al. (2011) applied BIM in sustainable design and LEED certification, and found that BIM saves time and resources in LEED certification by extracting credits directly, semi-directly, and indirectly using BPA and BIM software. Another study showcased a rule-based system embedded in an BIM model for automatically evaluating building sustainability according to LEED standards (Zhang and Chen, 2015). Chen and Nguyen (2015) demonstrated that 2 LEED credits (SSc2: Development Density and Community Connectivity and SSc4.1 Alternative Transportation – Public Transportation Access) can be efficiently achieved through BIM technology. Jrade and Jalaei (2013) proposed a modeling methodology that integrates BIM, LCA tools, and a sustainable materials database in order to enable stakeholders to earn LEED points. Jalaei and Jrade (2015) also described in detail how to integrate BIM with Canadian LEED certification. Their methodology automatically calculates LEED certification credit points and the associated costs of green certification materials. However, this study exclusively focused on EA and MR credits. Wong and Fan (2013) demonstrated that BIM could potentially facilitate LEED assessment and certification through a number of avenues. More specifically, they highlight that BIM authoring tools (such as Revit) can be used to select the best building orientation while BIM-based BPA software (such as Ecotect) can aid in compliance with the LEED rating system by assisting with shading analysis, solar design, lighting design, thermal performance analysis, ventilation and resource management. In addition, the authors suggest that Autodesk Green Building Studio (GBS) could be employed to assess multi-design alternatives. Wu and Issa (2012) proposed a cloud-based BIM server that stakeholders could leverage to achieve LEED automation. In a later, arguably more ambitious endeavor, Wu and Issa (2014) adapted BIM project execution planning guidelines (PEPG) to develop an integrated green BIM process map to address the specific requirements of implementing BIM in LEED projects (Wu and Issa, 2014).

Wong and Kuan (2014) created a framework that integrates BIM with Hong Kong's sustainable building rating system, BEAM Plus. They verified the framework through a public housing construction project case study as well as with a Delphi study demonstrating that BIM documentation could support earning 26 out of 80 credit points in BEAM Plus certification. Zanni et al. (2014) discussed the synergies between BIM, building performance analysis (BPA), and the UK established construction project plan of work RIBA and BREEAM green building rating system. The authors concluded that

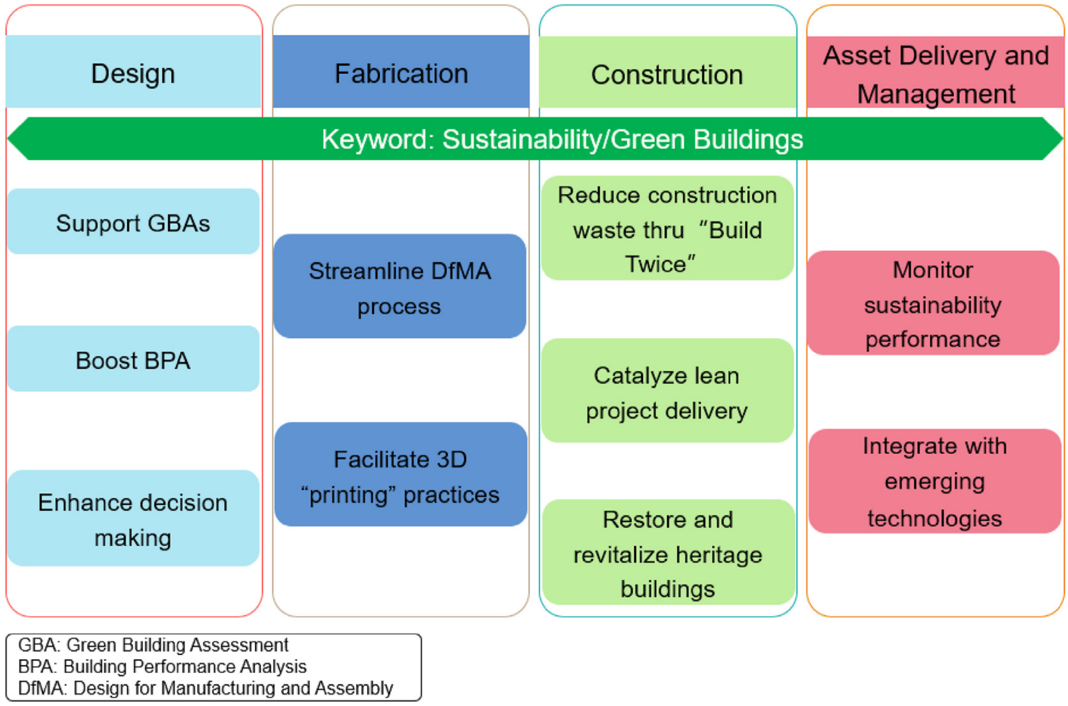

Fig. 10. Conclusive observations of BIM-sustainability in four IDD lifecycle phases.

BIM could be used in some categories of BREEAM such as emissions reduction, external lighting, low and zero carbon technologies, energy efficient transportation systems, and energy efficiency systems. Ilhan and Yaman (2016) developed a green building assessment tool (GBAT) to extract the required data from BIM to evaluate the level of the sustainability for BREEAM and provide feedback for further assessment.

5.1.2. Boosts building performance analysis (BPA) and simulation

BIM offers accurate geometric information and parameters. More accurate leveraging of BIM and efficient analysis processes are expected to be developed (BCA, 2015). Recently, Lu et al. (2017) summarized major BIM functions in regards to energy and sustainability performance. Various BIM-based BPA applications have been developed to assist in conducting various components of sustainability analysis during the design stage, such as energy performance analysis (Abanda and Byers, 2016; Sanhudo et al., 2018; Schlueter and Thesseling, 2009; Shadram et al., 2016; Shrivastava and Chini, 2012), carbon dioxide analysis (Basbagill et al. (2013); Knight and Addis, 2012) daylighting analysis (Andrews et al., 2011; Kota et al., 2014), thermal comfort analysis (Marzouk and Abdelaty, 2014), and water usage analysis (Martins and Monteiro, 2013).

- Energy efficiency analysis

Most energy analysis tools are designed to predict building energy performance. Abanda and Byers (2016) investigated the impact of building orientation on energy consumption and assessed how BIM can be utilized to promote this process. Sanhudo et al. (2018) presented a systematic BIM-based approach for energy retrofitting. Schlueter and Thesseling (2009) presented a BIM-based tool to underpin the graphical visualization of instantaneous energy consumption and performance metrics. Shadram et al. (2016) proposed a BIM-based LCA framework that assesses the embodied energy associated with the building materials supply chain based on Environmental Product Declarations (EPDs) during the design phase. Shrivastava and Chini (2012) explored the potential of BIM tools to compare the parameters of materials to support the decision-making process of selecting environmentally friendly design.

- Carbon emissions analysis

Basbagill et al. (2013) explored the application of life cycle assessment (LCA) to early architectural design, so as to reduce the impact on the environment. They found that LCA can aid in decision making at an early stage in building design to achieve significant carbon footprint reduction. Knight and Addis (2012) described incorporating carbon dioxide data into BIM processes and recommended that embodied carbon accounting be used in conjunction with quantity surveying to determine the out-turn cost of a building.

- Other green building analyses

Andrews et al. (2011) developed a computer-based BIM framework to support integrated characterizations of lighting, water, energy, and indoor air systems in buildings. Kota et al. (2014) proposed a new method for incorporating the daylighting analysis tools Radiance and DAYSIM into a BIM environment. In another study a framework was proposed for integrating a wireless sensor network (WSN) with BIM to measure and record the temperature and indoor air quality in subway stations, enabling asset managers to partially monitor thermal comfort and inspect facilities (Marzouk and Abdelaty, 2014). Other research has explored the use of automated code-checking software for water network designs through IFC format (Martins and Monteiro, 2013).

5.1.3. Enhances decision making through design optimization

BIM is able to leverage cloud-based computing power to perform rule-based design exploration and optimization on different digital platforms to achieve data-driven results and simplify change propagation during development (BCA, 2019b).

For example, Rahmani Asl et al. (2015) developed a BIM-based Performance Optimization framework using visual programming tools Dynamo and Revit, enabling the integration of the rich information stored in parametric BIM with building performance simulation tools, making performance optimization easier to realize in the design process. Tang et al. (2019) reviewed 97 papers related to BIM and the Internet of Things, finding that computational BIM (e.g., Dynamo, Grasshopper) can be used to export BIM data into various database formats.

5.2. Vertical 2: digital fabrication

BIM has been proven to enhance fabrication in many respects such as in sustainability, productivity and safety (Ghafar et al., 1993; Nawari, 2012; Sakin and Kiroglu, 2017; Zhang et al., 2016). The following two key recommendations were made regarding the digital fabrication stage:

5.2.1. Streamlines the design for manufacture and assembly (DfMA) process

DfMA is a cutting-edge engineering method that enables on-site work to be conducted more safely with minimal impact on the surrounding environment (BCA, 2009). With BIM, downstream DfMA activities (e.g., procurement, transport, installation) are more comprehensively linked to upstream activities such as concept design stage and planning stage (BCA, 2016). Adopting BIM in the DfMA process can streamline design, offsite manufacturing, and on-site assembly, conferring a number of benefits such as reducing costs, saving time, decreasing waste, improving quality control, and boosting productivity (BCA, 2016).

BIM for offsite construction facilitates more reliable information exchange among project stakeholders, and improves information quality, thereby supporting more effective decision making (Nawari, 2012). Zhang et al. (2016) examine how the integration of BIM technology into the industrialization of construction can improve the performance of modular and industrialized construction. Ghafar et al. (1993) contended that implementing BIM could increase productivity and reduce construction waste in the fabrication process through improving collaboration and knowledge-sharing among AEC professionals.

5.2.2. Facilitates 3D “printing” practices

3D “printing” technology has obvious advantages in saving time, lowering costs, minimizing pollution, and reducing construction safety risks. BIM is at the heart of the 3D printing building movement, providing software to control the design and construction process. BIM can also serve as a means for synchronizing 3D “printing” systems. The 3D “printing” process includes 6 activities: BIM modeling, exporting to an STL format, slicing, layer combination, 3D printing and printed object (Sakin and Kiroglu, 2017). However, to date 3D “printing” cannot fully replace traditional construction methods, due to limitations in printing materials and printer size (Sakin and Kiroglu, 2017).

5.3. Vertical 3: digital construction

It is well known that the construction process impacts the environment in a variety of ways, such as generating noise, vibration, dust, smoke, and waste residue. Energy consumed during construction phase is an important part of energy consumption in whole life cycle of the building. Based on observations drawn from the literature, BIM has demonstrated the following advantages in terms of sustainability during the construction phase.

5.3.1. Reduces construction waste through “build twice”

“Build twice” refers to first building in a virtual environment, and then in a real environment (BCA, 2017). It allows stakeholders to virtually simulate the design and construction process of a building before actual execution. Construction waste is mainly caused by improper design and unexpected changes. Existing studies (Cheng and Ma, 2013; Porwal and Hewage, 2012; Won et al., 2016) have shown that BIM is an effective means for reducing construction waste. Cheng and Ma (2013) developed a system that in part extracts materials and volume from a BIM model to estimate renovation and demolition waste for planning waste removal, including recycling, using a simulated 47-floor residential building in Hong Kong to demonstrate the system. Porwal and Hewage (2012) proposed a one-dimensional cutting waste optimization technique based on BIM to analyze reinforced concrete and reduce waste by minimizing rebar trim loss. The authors validated their approach with a two-story reinforced concrete structure case study, with the results also demonstrating great cost-saving potential. Won et al. (2016) sought to quantify the amount of construction waste, potentially arising from design errors, that could be avoided by using a BIM-based design validation process. Based on an analysis of two South Korean project cases, they estimated that 4.3%−15.2% of construction waste could be prevented with the aid of BIM.

5.3.2. Catalyzes lean project delivery

A quality BIM model contains the resources required for each task, such as manpower, materials, and equipment. Accordingly BIM serves as the cornerstone for collaboration between the main contractor and various subcontractors, maximizing just-in-time management of resources, reducing unnecessary inventory management and time, improving production efficiency, and minimizing waste to achieve maximum value (Ahuja et al., 2017). Drawing upon a bibliometric analysis of 32 articles, Saieg et al. (2018) proposed paradigm related BIM, Lean and Sustainability/Green. In addition, the paradigm provides understanding by identifying and explaining hypotheticals interactions that are primarily design-related activities and construction processes that clearly have strong synergies.

5.3.3. Restores and revitalizes heritage buildings

The use of BIM for sustainable restoration of heritage buildings has been studied through a number of research projects (Chiabrando et al., 2016; Khodeir et al., 2016). Using BIM in the historical field is considered to be the fundamental stage towards the BIM workflow for retrofit and reconstruction tasks. In this regard, Khodeir et al. (2016) outlined a conservation framework which integrates Heritage BIM (HBIM) into the sustainable retrofitting of heritage buildings.

5.4. Vertical 4: digital asset/facility delivery and management

Proper maintenance of building assets is conducive to promoting resource conservation, reducing the energy consumption, improving the energy efficiency of buildings in operation, and providing a safer and cleaner living environment for daily life. Using BIM for asset management and/or facility management improves the productivity of the operations through easing the retrieval of asset information to underpin decision making in building operation and maintenance. Furthermore, BIM facilitates better scheduling of assets, maintenance, repair and renovation work simply through visual inspection as many of the building elements or systems are physically clustered together (Building and Construction Authority, 2018). The following observations were made in digital asset delivery and management stage.

5.4.1. Monitor sustainability performance in real-time

Jiao et al. (2013) highlighted that BIM data is frequently modified, then delivered, archived, and occasionally accessed primarily for facility management. Kivits and Furneaux (2013) argued that BIM enables sustainability and asset management through knowledge management. A BIM-based framework was presented to support existing complex university building operations, maintenance, and sustainability (McArthur, 2015). By summarizing the relevant studies of ancestors, the four key challenges for sustainable operation and management are highlighted:

(1) Identifying the critical information required to support operational decisions;
(2) Creating new or modifying existing BIM models for the buildings;
(3) Managing information transfer between real-time operations and monitoring systems and the BIM model, and
(4) Handling uncertainty due to incomplete documentation.

To address some of these challenges, An integrated knowledge-based building management system was proposed using nD BIM applications (BIM-IKBMS) for inspecting post-construction energy efficiency (GhaffarianHoseini et al., 2017). McGlinn et al. (2017) presented a building energy management solution – BuildVis during FM stage which uses semantic and relational database technology to integrate BIM, sensor data, and actuator infrastructure. Marzouk and Abdelaty (2014) developed a framework for integrating a wireless sensor network (WSN) with BIM to measure and record facility humidity and temperature to partially monitor thermal comfort and enable asset managers to inspect facilities. Petri et al. (2017) illustrated the impact of BIM in the operational phase of a building with a focus on energy efficiency through a case study and it demonstrates the benefits of BIM in energy efficiency with respect to several energy metrics.

5.4.2. Integrate with emerging technologies

Yamamura et al. (2017) proposed the detailed assessment process for assessing urban energy performance using BIM and GIS. Shi et al. (2016) developed a multi-user VR system that allows real-time interaction between remote stakeholders such as facility managers, vendors, and designers in a virtual common data environment during the FM stage. Bottaccioli et al. (2017) proposed

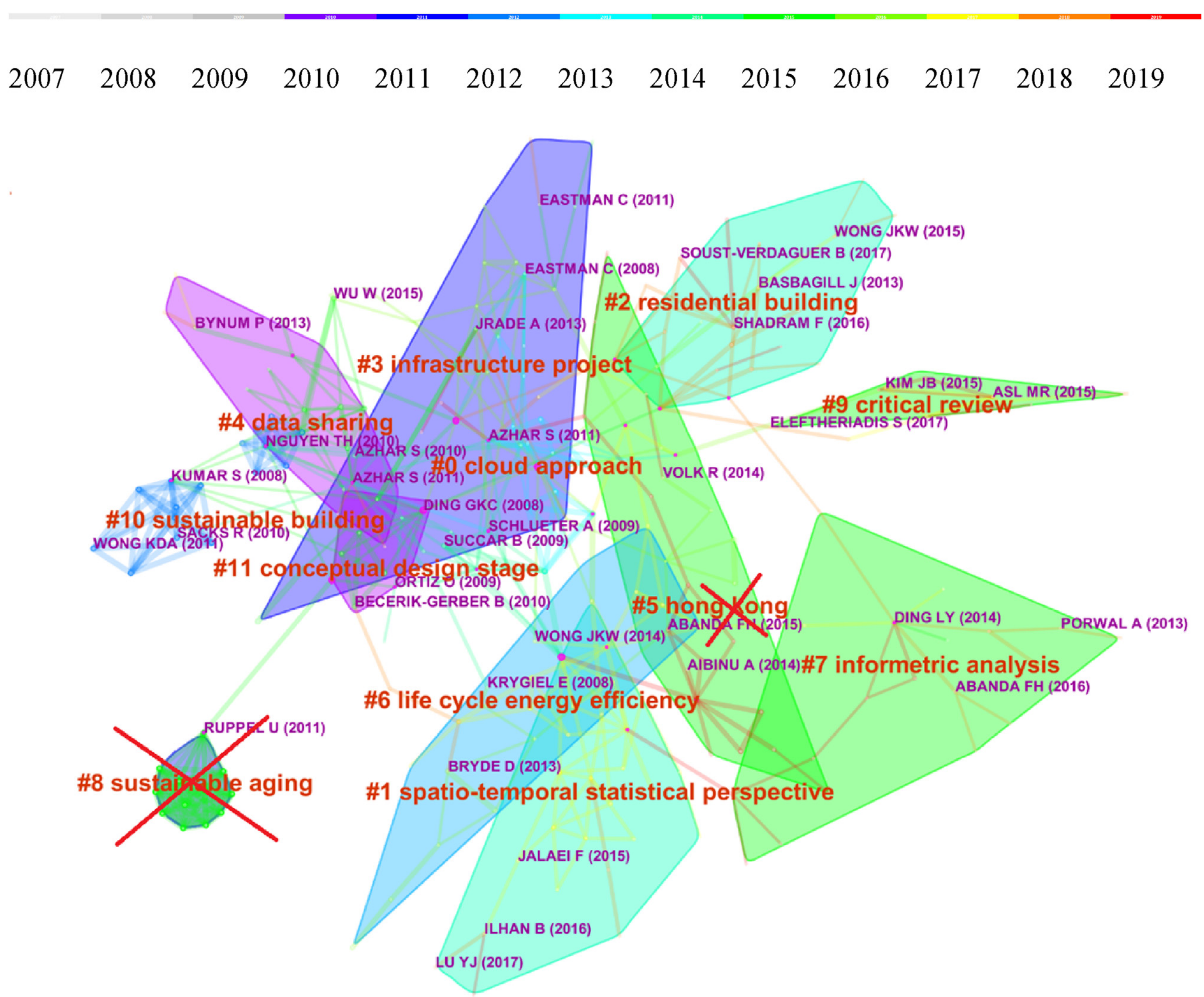

Fig. 11. Document co-citation clusters.

- Cluster #0 "cloud approach"

Table 8
Co-citation clusters of BIM for sustainability research in 2007–2019.

Cluster ID	Size	Silhouette	Mean Year	Cluster Label (LLR)	Alternative Label	Representative Documents
#0	30	0.63	2009	Cloud approach	Facilities management	Azhar, 2011; Schlueter and Thesseling, 2009; Succar, 2009
#1	24	0.927	2014	Spatio-temporal statistical	Knowledge-based building management system	Jalaei and Jrade, 2015; Lu et al., 2017; Ilhan and Yaman, 2016
#2	23	0.932	2014	Residential building	Early stage	Wong and Zhou, 2015; Basbagill et al., 2013; Shadram et al., 2016; Soust-Verdaguer et al., 2017
#3	23	0.764	2011	Infrastructure project	Digital collaboration technologies	Eastman et al., 2011; Jrade and Jalaei, 2013; Eastman et al., 2008
#4	22	0.792	2010	Data sharing	Sustainable building assessment	Azhar et al., 2011; Bynum et al., 2013; Nguyen et al., 2010; Azhar et al., 2010
#6	19	0.836	2012	Life cycle energy efficiency	Current development	Bryde et al., 2013; Krygiel, 2008; Wong and Kuan, 2014
#7	18	0.892	2015	Informetric analysis	Sustainable construction	Ding et al., 2014; Porwal and Hewage, 2013; Abanda and Byers, 2016
#9	11	0.946	2015	Critical review	Green building	Kim et al., 2015; Rahmani Asl et al., 2015; Eleftheriadis et al., 2017
#10	10	0.987	2009	Sustainable building	Sustainable design	Sacks and Barak, 2010; Kumar, 2008; Wong et al., 2011
#11	10	0.797	2010	Conceptual design stage	integrating building information modeling	Ortiz et al., 2009; Becerik-Gerber and Rice, 2010; Ding, 2008

integrating BIM, IoT, GIS and meteorological services to manage and simulate the energy behaviour of the building. The integration can be used in real-time monitoring and simulation to predict energy consumption. The proposed integration of BIM with augmented reality (AR) towards an intelligent environment for facility management, whereby mobile, user interfaces would provide the users with required data to underpin the critical decision-making process (Irizarry et al., 2014).

6. Cluster analysis for identification of research gaps and directions

6.1. Identification of key co-citation clusters

Co-citation cluster analysis is used to identify the themes and discover the knowledge hidden in the textual data (Zhong et al., 2019). Latent semantic indexing (LSI), log-likelihood ratio (LLR) and mutual information (MI) are the three clustering algorithms provided by Citespace toolkit (Chen, 2019). The LLR algorithm was adopted in the present clustering analysis. Silhouette is an indicator used in cluster analysis to measure the mean homogeneity of the clusters (Rousseeuw, 1987). A high silhouette score indicates that cluster members have high consistency among clusters of similar sizes (Rousseeuw, 1987). The silhouette scores of the above clusters ranged from 0.630 to 0.987, which indicates that the members of each cluster are consistent enough. Fig. 11 shows the change of research themes from 2007 to 2019. The results are indicated in Table 8.

The quality of the identified cluster depends on the breadth, variety, and depth of the set of terms from the keywords in the cited references or documents (Olawumi and Chan, 2018). The label generated by each identified cluster represents the focus of the cluster. However, the data examined with cluster analysis include the documents cited in the 471 articles, which may contain some articles irrelevant to the topic. Therefore, manual review of article content was conducted to remove unrelated clusters. As shown in Fig. 11, cluster #5 "Hong Kong" and cluster #8 "sustainable age" were removed due to its degree of aggregation being relatively small and having little correlation with BIM-sustainability.

As shown in Fig. 11 and 30 members were labeled as Cluster #0 "cloud approach", wherein the three representative publications were Azhar (2011), Schlueter and Thesseling (2009), and Succar (2009). Azhar (2011) (frequency = 44) proposed that BIM could provide a virtual environment for simulating a construction project. Azhar (2011) also forecasted that the growing application of BIM will strengthen cooperation amongst practitioners in the AEC industry by reducing fragmentation and improving project cost performance. In addition, Azhar suggested that the AEC industry in the United States regards BIM-based BPA tools as a more cost efficient and time saving approach than conventional methods. Although the BIM-green building framework is proposed in this study, a remaining concern is that the cloud based common data environment to facilitate green building assessment process and rule based auto-checking needs to be further studied. Schlueter and Thesseling (2009) (frequency = 32) highlighted that building simulations are usually carried out after decision-making at early design, hence it is necessary to incorporate simulation into the design phase. They also presented visualization of instantaneous energy consumption as well as the resulting performance metrics using a BIM-based prototypical tool. Due to the complex dependencies of virtual environment modeling, it is necessary to develop an innovative approach that regards building as a whole system. While this study did not discuss the issue further. Succar (2009) (frequency = 25) developed a BIM framework to support decision making across the building lifecycle from design to the facility management stage. However, further research is still needed to enrich the BIM framework and industrial deliverables.

- Cluster #1 "Spatio-temporal statistical"

24 members were categorized in Cluster #1 "Spatio-temporal statistical", in which the top three publications were Jalaei and Jrade (2015), Lu et al. (2017), and Ilhan and Yaman (2016). Jalaei and Jrade (2015) (frequency = 25) described a method of integrating BIM with the Canadian green building certification system (LEED). This study paved the way for the automatic assessment of the sustainability level throughout the life cycle of design. Lu et al. (2017) (frequency = 20) critically reviewed the nexus between BIM and green buildings on the basis of academic researches and industrial exercises. They proposed a green BIM triangle taxonomy that categorizes the connection of BIM and green buildings through BIM attributes, green attributes, and project phases. Ilhan and Yaman (2016) (frequency = 18) developed an assessment tool (called GBAT) to extract data from BIM to evaluate the level of sustainability for BREEAM and provide feedback for further assessment of green buildings.

- Cluster #2 "Residential building"

17 members were found in Cluster #2 "Residential building",

where Wong and Zhou (2015), Basbagill et al. (2013), Shadram et al. (2016) and Soust-Verdaguer et al. (2017) were the top four representative articles. Wong and Zhou (2015) (frequency = 44) carried out a critical review to compare 84 peer-reviewed articles related to Green BIM in which 44 articles focused on the design phase, 25 on the construction phase, 8 on the facilities maintenance and retrofitting phase, and 12 on the end-of-life phase such as demolition. The authors also integrated big data within a cloud-based BIM for green building sustainability management, enabling lifecycle environmental monitoring and management in the future. However, in view of the three main deficiencies of the reviewed green BIM literature, their review only proposed a general approach for improvement, while lacking specific problem descriptions and targeted solutions. In this regard, Basbagill et al. (2013) also explored the application of lifecycle assessment to minimize the environmental impact in early architectural design. In addition, LCA was used in multi-building residential development. Their findings indicated that BIM can improve the building design process by emphasizing the early-stage decisions that lead to the most significant embodied carbon reduction. Shadram et al. (2016) (frequency = 20) proposed a BIM-based LCA framework that follows Environmental Product Declarations (EPDs) during design to assess the material embodied energy. Soust-Verdaguer et al. (2017) reviewed the research of BIM-based LCA in recent years and made a methodological analysis of its integration with the emphasis on simplifying data input as well as optimizing output data and results in the application of BIM in building LCA. Their results show that it is feasible to develop BIM model-based methods for organizing building lifecycle information through the assessment of environmental impacts and energy consumption. Yet LCA is only applied to the BIM development plug-in in a small range with a few environmental indicators (such as carbon dioxide emissions), and does not involve the application examples of the entire BIM-based LCA.

- Cluster #3 " Infrastructure project"

23 members were categorized as Cluster #3 " Infrastructure project "in which Eastman et al. (2011, 2008) and Jrade and Jalaei (2013) were the most cited. Among these documents, two were BIM handbook (frequency = 69 and frequency = 27) published by (Eastman et al., 2008), (Eastman et al., 2011). In addition, Jrade and Jalaei (2013) (frequency = 29) presented a method leveraging BIM and LCA for designing sustainable construction projects. The proposed method leverages a database to store and link information on sustainable materials with 3D BIM, LCA, and authentication and cost module. One main limitation of the proposed method is that it cannot be applied to the design phase of a construction project, because its integrated database only stores information about commonly used components of construction projects.

- Cluster #4 "Data sharing"

22 members were categorized as Cluster #4 "data sharing". The top four representative articles were published by Azhar et al. (2011), Bynum et al. (2013), Nguyen et al. (2010) and Azhar et al. (2010). Azhar et al. (2011) (frequency = 66) proposed and validated the conceptual framework of BIM and LEED-based sustainable analysis through a case study. The authors demonstrated BIM in sustainable design and LEED® certification, the results of which suggesting that BIM-based sustainability analysis software can directly or indirectly prepare files to support LEED scoring. This study also verifies that the framework can simplify the verification of LEED® and save a lot of time and resources compared with conventional methods. However, due to the lack of integrated functionality of LEED® in currently available software, there is no one-to-one relationship between the LEED® certification process and BIM-based sustainability analysis. In addition, there are some differences between the software and manual results, which lower the accuracy of BIM. Bynum et al. (2013) (frequency = 24) carried out a profound literature review of BIM, sustainable built environment, green building assessment organizations and relationship between BIM and sustainability, and they investigated trends in BIM application in general and in sustainable design and construction specifically with the research method of on-line survey. The results of the study show that the majority of interviewees believe that sustainable design and construction practices are important in their companies, but it is not the main application of BIM in the eyes of most people. On the contrary, project coordination and visualization are more important. Nguyen et al. (2010) (frequency = 6) developed a sustainability assessment framework using BIM in extracting data from BIM to assess the sustainability level based on LEED. The applicability of the developed framework was verified through a hotel project. In the future, the research should involve all factors related to the construction process in the entire project life cycle to solve the complex interrelationships in sustainability, making the results more convincing and reasonable. Azhar et al. (2010) (frequency = 6) found that BIM provides significant opportunities to perform building analysis and to optimize the design. Furthermore, the authors observed that BIM also can be used to generate necessary documentation for LEED certification during the design stage.

- Cluster #5 "Hong Kong"

As indicated in Fig. 11, Cluster #5 was removed due to the members in this cluster have a little correlation with BIM-sustainability.

- Cluster #6 "Life cycle energy efficiency"

19 members were found in Cluster #6 "Life cycle energy efficiency". Bryde et al. (2013) (frequency = 40) discussed the beneficial use of BIM for 35 building construction projects and identified critical successful factors, with the aim of determining the compliance of every project to the factors. The greatest benefits reaped due to the use of BIM software were the cost reductions and control achieved across the project lifecycle. Key challenges due to the use of BIM were also identified, including education, training, improvement of awareness, and cost/benefit analysis. Krygiel (2008) (frequency = 25) published the Green BIM book and introduced how to realize sustainable design using BIM. Wong and Kuan (2014) (frequency = 22) explored combining BIM with the sustainable building rating system BEAM Plus through a case of a Hong Kong residential building project. They found that 26 out of 80 points in BEAM Plus could be garnered with the support of the documentation produced by BIM. Nevertheless, it is only a preliminary study on the application of BIM-BEAM Plus. Further validation of the results from BIM-BEAM Plus with real projects is needed.

- Cluster #7 "Informetric analysis"

There were 18 members in the Cluster #7 "Informetric analysis". Ding et al. (2014) (frequency = 20) was the most frequently cited, in which the applications of BIM on safety, project quality control, and environmental management were discussed. The study also illustrates the evolution of 3D BIM to nD models, especially with the integration of quality, safety, and carbon emissions. Porwal and Hewage (2013) (frequency = 16) proposed a "BIM Partnering" public procurement framework to guide collaboration between private sector contractors and public sector clients. The proposed project within the contract scope would lead to increased productivity and better coordination along with a reduction in errors and rework. Their case study verified the significant improvement in the cost, value, and carbon performance can be achieved on public construction projects by 'model analyses' through the proposed "BIM-partnering "process. Abanda and Byers (2016) (frequency = 11) investigated the impact of building orientation on energy consumption and assessed how BIM can be used to facilitate this process.

- Cluster #8 " Sustainable aging"

As indicated in Fig. 11, Cluster #8 "Sustainable aging" was removed due to it containing relatively few representative articles.

- Cluster #9 "Critical review"

There were 11 members in Cluster #9 "Critical review". The top three documents were published by Kim et al. (2015), Rahmani Asl et al. (2015) and Eleftheriadis et al. (2017). Kim et al. (2015) (frequency = 14) proposed an Object-Oriented Physical Modeling (OOPM) approach using BIM to enable data exchange between building design and energy simulation software. However, the research lacks specific examples of data exchange, that is, it does not identify which building components need to be modified or how the components can be modified to connect with the energy module for the purpose of achieving the desired energy saving goals. Similarly, Rahmani Asl et al. (2015) (frequency = 14) presented a BIM-Based Performance Optimization (BPOpt) tool to evaluate and analyze the energy performance of various design alternatives. A Cloud-based simulation and visual programming user interface were used to assess design effects on building energy consumption. Eleftheriadis et al. (2017) (frequency = 12) explored decision-making procedures within BIM including optimization methods, buildability and safety constraints, and code compliance limitations at early stages. The authors affirm the utility of BIM to aid in resolving the tensions between energy efficient and engineering performance indexes.

- Cluster #10 "Sustainable building" with focusing on education

Cluster #10 "Sustainable building" contained 10 members. The top three documents were published by Sacks and Barak (2010), Kumar (2008) and Wong et al. (2011). Sacks and Barak (2010) (frequency = 4) made a list of universities that have incorporated BIM into their civil engineering curriculum and observed that although BIM represents the major content of the course listed, it enables graduates to meet the needs of the civil engineering profession in the "BIM age". Kumar (2008) (frequency = 4) expressed that the ideal interoperability should be a seamless exchange between BIM software to avoid duplication of data. It should also provide bidirectional updating of data, with changes in one program being capable of flowing between other associated programs. But this study did not discuss the impact of improved interoperability on sustainable buildings as part of the case for interoperability. Wong et al. (2011) (Frequency = 2) discussed initiatives undertaken by the Hong Kong Polytechnic University to incorporate BIM in its course curricula.

- Cluster #11 "Conceptual design stage"

There were 10 members in Cluster #11, "Conceptual design stage". The top three representative articles were published by Becerik-Gerber and Rice (2010) and Ding (2008). Ortiz et al. (2009) (frequency = 9) reviewed the literature from 2000 to 2007 on LCA studies conducted for sustainability evaluation of residential buildings, commercial buildings, and civil engineering constructions. The authors paid specific attention to LCA as applied more narrowly to building materials and components versus over the entire construction project. Becerik-Gerber and Rice (2010) (frequency = 6) conducted a survey to examine the perceived value of BIM in the US AEC industry, with a focus on the tangible benefits and costs of BIM application at the project level. However, the intangible and semi-tangible costs and benefits related to BIM were not mentioned in this study, and there was also a lack of detailed analysis of cost reduction. Ding (2008) (frequency = 4) examined the development, role, and limitations of contemporary environmental building assessment methods in various countries, which provided a launchpad for exploring and developing a multi-dimensional sustainability model before the design phase and instead at the initial project appraisal stage.

6.2. Research gaps and future study

Although BIM has demonstrated many advantages in the vertical level (design, fabrication, construction, and AM/FM phases), research gaps still exist, especially at the horizontal level. Using a comprehensive and systematic IDD thematic discussion and cluster analysis of the literature related to BIM-sustainability, research gaps and possible research directions were identified and sorted into five main categories. These include: (1) discrepancies in life cycle data exchange and model interoperability—especially between BIM authoring software and BPA software [clusters 0, 1, 4, and 11], (2) lack of a holistic total building performance framework to support BIM-sustainability building assessment processes [cluster 7 & IDD Observation 2]; (3) Tedious, silos and non-collaborative processes for green building assessment [Cluster 2 and Observation 1] and (4) Infancy stage: insufficient support of BIM for sustainable FM [IDD Observation 9 and 10], as summarized in Fig. 12.

Interoperability across the life cycle remains a fundamental challenge in IDD, especially in the transfer of data from an BIM authoring tool to Building Performance Analysis (BPA) software. BIM has played a central role coordinating the work of different industry practitioners in the AEC industry. Its underlying data standard, i.e., Industry Foundation Classes (IFC) (buildingSMART, 2019), has been demonstrated to be useful for various green building analyses and simulations. Leveraging transferring BIM to BPA approach contributes to accurate and efficient analytical processes (BCA, 2015). Currently, green building Extensible Markup Language (gbXML) (gbXML Schema, 2020) is the most prevalent information exchange format in the AEC industry (Chong et al., 2017). However, transferring essential BIM data through IFC or gbXML can hardly be directly applied to specific building performance analysis (Bynum et al., 2013; Cheng and Das, 2014; Geyer, 2012; Hassan Ibrahim, 2013; Jrade and Jalaei, 2013; Lu et al., 2017) and may result in substantial data loss (Ansah et al., 2019).

Karan and Irizarry (2015) argued that the IFC schema lacks an energy domain and that an extension should be developed to facilitate green data exchange. Most errors during data transfer are caused by differences in the initial BIM model setup and modeling rules, not by the processing of IFC files (Cemesova et al., 2015). The IFC data model allows for customization of properties in the existing list of classes. Therefore, some "localization" can be carried out on top of the IFC standard to capture information of interest that is unique to the green building assessment. This localized IFC data model is developed based on the IFC standard to address the sustainability assessment such as LEED, BREEAM, BEAM plus and so on.

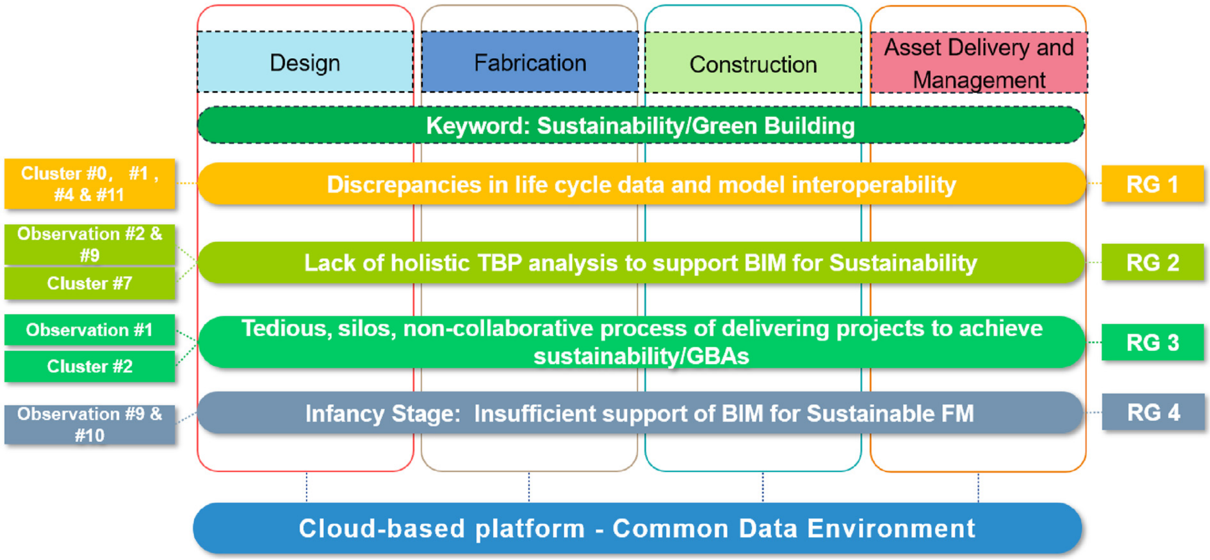

Fig. 12. Research gaps across IDD.

- Research Gap 1: Discrepancies in life cycle data exchange and model interoperability

gbXML is a common format to facilitate data transfer between BIM and BPA software. It is an XML-based extension, a non-proprietary protocol which allows customization of markup languages for exchanging information within various domains (Dong et al., 2007). However, gbXML has its drawbacks. One is that it is only able to capture rectangular shapes in geometric information (Jalaei and Jrade, 2014). Another is that gbXML is not yet adequately developed to identify and interpret sustainability information specific to BIM-based green building assessments (Ansah et al., 2019). Therefore, interoperability deserves further study in the future. Furthermore, as recommended by Ansah et al. (2019), future research should perhaps be extended beyond IFC and gbXML to explore the potential of other file formats for transferring and managing various types of data.

- Research Gap 2: Lack of a holistic TBP framework to support BIM-sustainability

As described in section 5.1.2 Observation # 2, BIM boost BPA, existing research mainly focuses on the integration of BIM with unitary and isolated building performance analysis, such as energy, lighting, or water analysis. However, a holistic framework that integrates total building performance (TBP) with IDD seems to be missed from previous studies.

- Research Gap 3: Tedious process of delivering projects to achieve sustainability/GBAs

The 3rd gap is the tedious process of compiling the required green building assessments (GBAs) and cumbersome documentation management. The current process of delivering a project for green building assessment is considered to be tedious and cumbersome, which hampers productivity (Ansah et al., 2019; Geyer, 2012; Wong and Kuan, 2014; Wu and Issa, 2012). The process normally involves multiple stakeholders working in silos and in a non-collaborative, manual, 2D-based environment for generating relevant documentation to achieve the green building certifications. In addition, the traditional process is often error-prone and inaccurate and might lead to the loss of important information related to sustainability. BIM provides semantic and geometry information of buildings and allows project stakeholders to work in a common environment (Wu and Issa, 2010). Future research could investigate the common data environment (CDE) to assist sustainability/GBAs.

- Research Gap 4: Insufficient support of BIM for Sustainable FM

Using BIM for Facility Management remains limited at the digital asset delivery and manage at the infancy stage. There are three main reasons: (1) lack of awareness of the applicability of BIM to FM (especially a lack of understanding of its benefits). (2) lack of clear definition of data exchange for FM and (3) lack of clearly defined use cases in compliance with industry standards/guidelines for practitioners to follow (Dong et al., 2014). Another reason: (4) As-built BIM models not adequate for facility or asset management purposes due to lack of AM or FM data. In addition, some of the data used for design, construction and fabrication are not useful for AM/FM purposes. Becerik-Gerber and Kensek also highlighted that barriers to using BIM for FM include a lack of software interoperability and a dearth of scientific studies that quantify the value of BIM to FM (Becerik-Gerber and Kensek, 2010).

IDD and sustainable building are at the core functionally complementary. Achieving sustainable building requires a full grasp of all the green attributes of different materials and equipment, as well as coordination and optimization across the entire project cycle in order to save energy and reduce emissions. A cloud-based CDE that encourages such data consolidation and coordination among various stakeholders could be a major avenue for bridging the four identified research gaps.

7. Research contributions

This study reveals IDD as a new solution for tackling the challenge of building BIM for lifecycle management and sustainability of buildings. Yet few studies have done the review work in past research on BIM-IDD for sustainability research. BIM has demonstrated multiple advantages throughout the IDD lifecycle (i.e., design, fabrication, construction, and asset management/facility management). However, there are still several obstacles to information transfer between phases, such as inconsistencies in file structures during data exchange, insufficient BIM parameters for covering the entire lifecycle, the absence of a framework for the integration of processes and stakeholders, and the tremendous complexity of LCA. This research suggests that IDD can serve as an effective enabler to improve the performance of BIM for lifecycle management and sustainability. That is, adopting IDD can offer access to upgrading 5D BIM to 6D BIM. As a knowledge discovery framework, IDD can identify and trace potential correlations between different BIM attributes.

In addition, a new visualization method is proposed for reviewing the literature on BIM-sustainability. Knowledge extraction from different sources and documents and citation burst identification were achieved using a combination of co-citation network and thematic theme analysis. The scientometrics analysis can improve the understanding of BIM-sustainability issues for academics and industry, demonstrate the stereoscopic space of these issues, and establish correlations among otherwise seemingly unrelated issues. Moreover, graph theoretical approaches to social network analysis can help scholars and practitioners understand relationships between literature produced by different researchers and institutions and from different perspectives, as well as chart the historical development, research gaps, and future trends of BIM research.

8. Conclusions

In this paper, BIM-sustainability was critically reviewed and Citespace was adopted to analyze 471 documents obtained from the WoS database. The results include network analysis, co-occurring network analysis, and co-citation network analysis in order to identify the current research status, gaps, and future trends, in this field. This study provided visualization analysis of 471 publications related to BIM-sustainability through scienometric analysis and reviewed the top 100 most cited publications. The concentrated clusters and observations throughout the IDD life cycle were summarized and categorized. The present study provides a handy overview of the current state of research on the topics of the past 11 years and points out future research directions. The main findings are as follows:

- Since 2014, the number of publications has a significant yearly increase, and the total amount has reached over 80%. The most prolific countries/regions are China, USA, and England. Keywords such as “BIM”, “Sustainability”, “Design”, “Construction” and “Life Cycle Assessment” are frequently mentioned, while “Interoperability”, “Life Cycle Assessment”, “Energy”, “Construction Project” and “Simulation” are keywords with high centrality. These keywords are consistent with the main research topics obtained by IDD cluster analysis.
- The document co-citation clusters were generated and it include #0 Cloud approach, #1 Spatio-temporal statistical, #2 Residential building, #3 Infrastructure project, #4 Data sharing, #6 Life cycle energy efficiency, #7 Informetric analysis, #9 Critical review, #10 Sustainable building and #11 Conceptual design stage.
- The top 100 most cited documents were summarized into four IDD themes, including digital design (V1), digital fabrication (V2), digital fabrication (V2), digital construction (V3) and digital asset delivery and management (V4). According to IDD quadrants, four future research directions were summarized.

Inevitably, this research has certain limitations. First, bibliographies in this review were obtained from WoS only, and data from other academic databases (e.g., Scopus, EI Village, Elsevier and EBSCO) were not included for analysis. Second, the search field used in the present study was restricted to “Title” instead of “Title/Abstract/Keywords” in order to prevent an immoderate amount of invalid records being returned. Third, only English document types limited to article type, proceeding papers, reviews, and early access were reserved, while book reviews, news items, and editorial material were excluded. The statistical results of this study might be affected by these limitations, but the impact these set boundaries have on characterizing future research trends and IDD thematic discussion is likely slight. Future studies can expand beyond these limitations by broadening the scope of literature to different databases and languages to deliver more generalized insights.

Disclaimer

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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